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Generation of Intense PEFs Using a Prolate Spheroidal Reflector Attached to the Bipolar Former of a 10-GW Pulsed Power Generator

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Abstract—A prolate spheroidal reflector was designed, manufactured, and attached to a bipolar former at the output of a 10-GW-Tesla-driven Blumlein pulsed power generator. The reflector, operated in water, is capable of producing intense pulsed electric fields of the order of 50 kV/cm. Constructional details are provided, together with experimental results, and a detailed analysis using 3-D software modeling of the reflector that provides results in good agreement with experimental data.

Index Terms—Antenna, pulse compression circuits, pulse modulation, pulsed electric fields (PEFs), pulsed power systems.

I. INTRODUCTION

A RANGE of modern pulsed power applications, including not only bioelectric studies and medical cancer treatment but also food industry processing and water sterilization, require the generation of intense pulsed electric fields (PEFs) in dielectric materials having a large value of permittivity.

Related to medical applications and using invasive electrode-based techniques, a number of research groups worldwide have successfully demonstrated that picosecond (ps) PEFs can induce apoptosis in cancer cells [1]–[4].

The use of ultrashort pulses with a rise time of the order of hundreds of ps provides also an opportunity of using noninvasive antenna techniques, instead of invasive electrodes, to deliver ps PEF to targets inside bodies. There are basically two possible configurations, both based on Carl Baum designs and pioneered at Old Dominion University, USA. In the first arrangement, a focusing antenna is placed in air and the very high electric fields are generated inside the biomedical target

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with the aid of a complex adapting impedance system made from a large number of lenses [5]. In the second arrangement, a prolate spheroidal reflector (PSR) is used and immersed in water to directly focus ps PEF inside a small volume of a target also placed in water [6].

This paper, representing the third phase of the Loughborough program aiming at developing noninvasive PEF systems, is using the second Baum arrangement. In the first phase, a 10-GW generator was built and tested [7], while in the second phase, a bipolar former (BF) was demonstrated to modulate and condition the generator voltage output to allow the efficient coupling to an antenna [8].

This paper presents the design, manufacture, and testing of a PSR. Experimental results are compared with predictions made using Computer Simulation Technology (CST) [9] 3-D modeling, before concluding remarks that include a brief comment on the next steps toward the development of a powerful ps PEF generator for medical applications.

II. DESIGN, MANUFACTURE, AND MODELING OF THE PROLATE SPHEROIDAL REFLECTOR

A. Design and Manufacture

The design of the PSR followed the technique described in [6] and the result is presented in Fig. 1. The PSR is immersed in water and coupled to the 50-Ω coaxial transmission line output of the existing BF [8]. Using a formula presented in [6], the characteristic input impedance of the PSR can be calculated as

$$Z = \frac{1}{\pi} \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \ln \left(\cot \left(\frac{\theta_0}{2} \right) \right) \quad (1)$$

where $\varepsilon_r = 2.4$, since, in the present arrangement, polyethylene fills the space between the reflector and the conical wave launcher (CWL) and θ_0 is its half-angle (see Fig. 1). For the design in Fig. 1, $\theta_0 \approx 21.3^\circ$ and therefore the input impedance of the PSR is $Z \approx 130 \Omega$. No efforts have been attempted at this stage to reduce the mismatch between the BF coaxial output and the PSR.

Manufacture of the PSR required a wooden frame to be built [Fig. 2(a)], after which 2-mm stainless steel sheet was used to obtain the required shape [Fig. 2(b)].

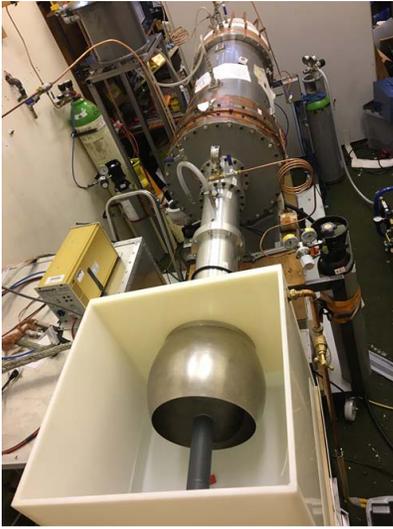


Fig. 4. Overview of the experimental arrangement, with the PSR mounted inside a plastic cube and the D-dot probe assembly mounted on its axis. During testing, the cube is filled with water.

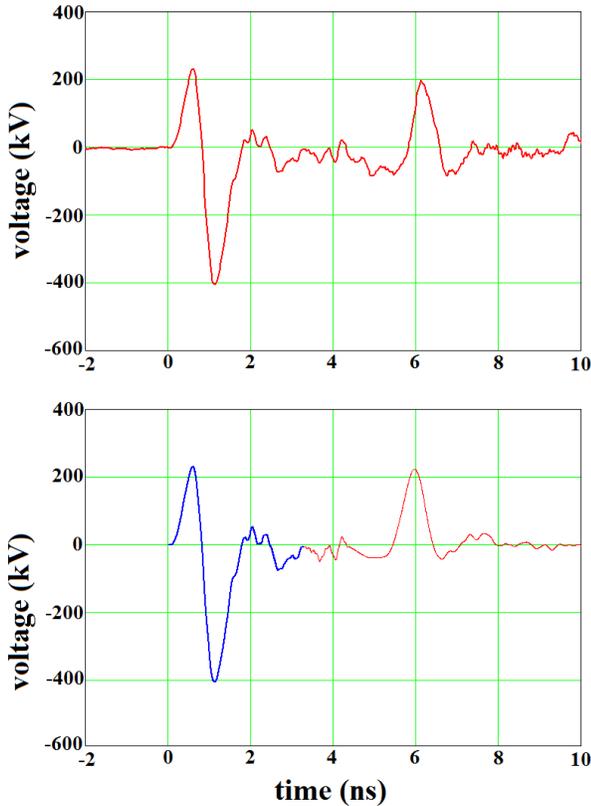


Fig. 5. Time variation of the voltage impulse in the 50- Ω coaxial transmission line connecting the BF with the PSR. Top: *experimental data*; bipolar voltage impulse measured by the V-dot attached to the coaxial transmission line. Bottom: *CST data*; the first 3 ns of the experimental voltage signal (highlighted) are used as CST input data. The rest of the voltage signal, including the voltage reflection (around 6 ns) due to coaxial line-PSR impedance mismatch, is predicted by CST.

The water can be continuously filtered in order to maintain a resistivity of 20 $M\Omega \cdot \text{cm}$.

For modeling the propagation of electromagnetic waves through water, a Debye model which takes into account the losses was readily available in the CST library.

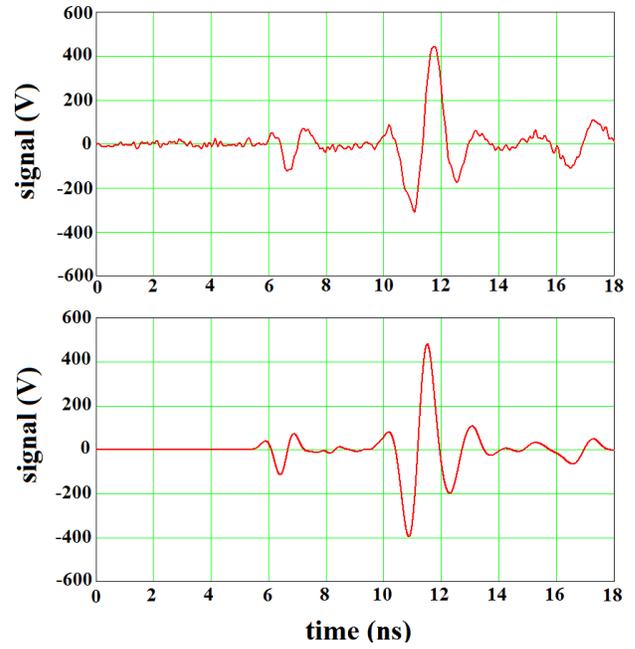


Fig. 6. Typical D-dot signal during a test (time origin as in Fig. 5). Top: *experimental data*; rough signal, as recorded. Bottom: *CST predicted data*.

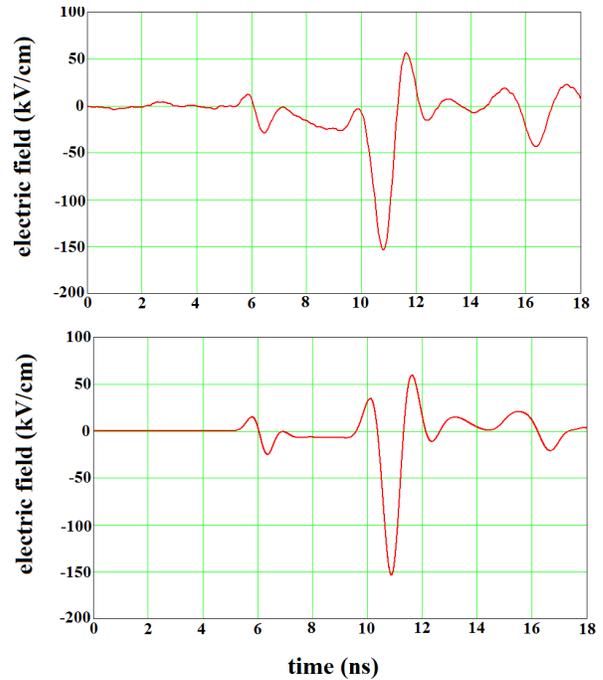


Fig. 7. Time variation of the electric field strength in water, near the D-dot probe polyethylene cover (time origin as in Fig. 5). Top: *integrated experimental data*. Bottom: *CST predicted data*.

III. EXPERIMENTAL RESULTS COMPARED WITH CST SOFTWARE PREDICTIONS

The main results obtained during the experimental campaign are presented in Figs. 5-7. The PSR is energized by the voltage impulse generated by BF shown in Fig. 5, with a (negative) time rate-of-change peak close to 2.5 MV/ns. Data from the first 3 ns of the voltage impulse, obtained by integrating the

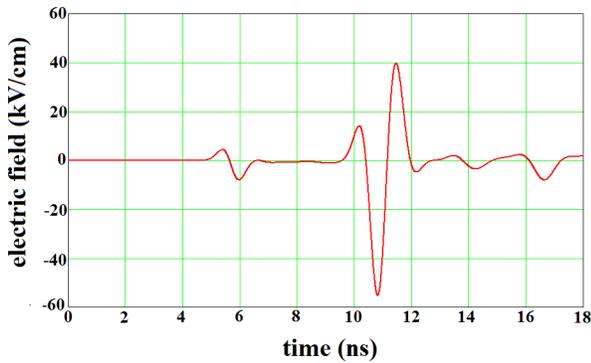


Fig. 8. CST predicted time variation of the electric field strength in water in the (second) PSR focus point, in the absence of the D-dot probe assembly (time origin as in Fig. 5).

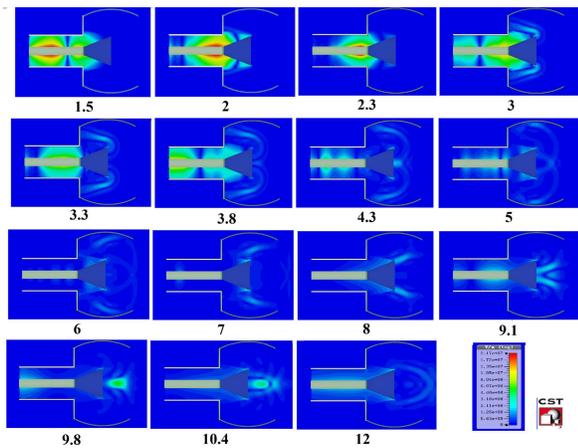


Fig. 9. CST predicted time variation of the electric field distribution in water and polyethylene, corresponding to Fig. 8 (stills from a movie). Numbers indicate the time in ns, with time origin as in Fig. 5.

time rate-of-change signal recorded from the V-dot probe, are used as input for the CST model. Due to the impedance mismatch between the coaxial line and the PSR, a reflected voltage impulse can be observed at about 6 ns, both on CST predictions and on the experimental data (Fig. 5).

The time rate-of-change signal recorded from the D-dot probe is shown in Fig. 6 and compared with the CST prediction. The integrated data, representing the electric field in water near the D-dot polyethylene cover, are presented in Fig. 7. A good agreement can be noticed between the experimental data and the CST calculations. This enables the CST to be used to predict the electric field, presented in Fig. 8, which is generated in the absence of the perturbing D-dot assembly in a cm^3 size spot surrounding the PSR (second) focal point [6]. The corresponding time variation of the electric field distribution is shown in Fig. 9, where one can distinguish the three types of waves described in [6]: prepulse at 5 ns, the impulse at 10.4 ns, and the superposition of the first two.

IV. CONCLUSION

A PSR was designed, manufactured, modeled, and attached to the BF of a 10-GW pulsed power generator, and was tested immersed in water. The results obtained indicate the

possibility to generate in water the peak electric fields in the order of 50 kV/cm.

The results open the way for interesting biomedical proof-of-principle experiments, allowing the system to be used in the near future for preliminary *in vitro* and *in vivo* testing.

In the next phase of the program, it is intended to develop a much more compact and efficient PEF system, capable of operating at a high repetition rate.

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